

International Journal of Quantum Information
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Quantum bit error rate in modeled atmospheres.

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The quantum bit error rate is a key quantity in quantum communications. If the quantum channel is the atmosphere, the information is usually encoded in the polarization of a photon. A link budget is required, which takes into account the depolarization of the photon after its interaction with the atmosphere as well as absorption, scattering and atmospheric emissions. An experimental setup for the reproduction of a simple model of the atmosphere is used to evaluate the quantum bit error rate in a BB84 protocol and the results are presented. This result represents a first step toward the realization of an optical bench experiment where atmospheric effects are simulated and controlled for reproducing the effects on a quantum channel in different meteorological situations.

Keywords: QBER; modeled atmosphere.

1. Introduction

Recent experiments have proven the feasibility of quantum communication in free space. In ¹, an experimental implementation of quantum key distribution over a 144 km free-space link is reported. In ², the first experimental study of the conditions for the implementation of the single-photon exchange between a satellite and an Earth-based station is accounted for.

The former experiment was located at a mean altitude of more than 2400 m, along an horizontal path over the sea and exploited a quantum communication protocol relying on decoy-states. Under good atmospheric conditions (where the authors

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do not specify the atmospheric parameters), a 10 dB attenuation was assumed to be due to atmospheric losses; with the further assumption that the eavesdropper could not exploit multiphoton pulses, a 28 bit/s bit rate and a 6.77% QBER were obtained. The latter experiment was carried out along a vertical downward path (from a satellite to the Earth); a 81% atmospheric transmission was estimated in accordance with the modeled atmosphere losses (according to ³, they match the losses in a clear atmosphere, at the experimented wavelength of 532 nm). A 157 dB total attenuation was observed and 4.6 counts per second were estimated.

The first remark we want to make on both experiments is the low bit rate: it is too low compared to the present request which may be as high as many Mb/s; thus neither of these two experimental results are useful, so far, to exchange a quantum key under desired operating conditions. Second, the quantum communication security decreases as the bit rate gets closer to the dark counts rate. For instance, in a BB84 protocol, the highest losses for a secure quantum transmission were estimated to be 40 dB⁴, which is far less than the losses obtained in ². Thus, a lot of work must be directed towards an improvement of the quantum key bit rate and of the error rate of the communication link.

To this end, enhancements can be made in the source and receiving devices, or studies can be carried out on the quantum communication channel and the latter option is investigated in this paper.

Furthermore, the realization of an operative Earth – space quantum channel will require the possibility using the system under different meteorological situations (e.g., in presence of haze or translucent clouds, such as cirri clouds) and when the satellites is at different angles from the horizon. Thus, the operativity of the system must be estimated under all these conditions.

Our purpose is to investigate and record the losses under different atmospheric conditions. Those will contribute, together with the other sources, to the final losses and to the final bit rate. Thus, before the actual communication takes place, one is able to know whether the quantum key exchange is feasible (by estimating the bit rate) and secure (by estimating the total losses), depending on the atmospheric conditions.

A full-scale experiment has two main drawbacks:

- (1) it is expensive,
- (2) it can not be created on demand.

Those disadvantages can be overcome by experimentation in laboratory. In this paper, we report on our first approach to model different atmospheres in laboratory and to estimate the QBER for a simple BB84 quantum communication protocol. We present preliminary results showing the feasibility of this approach, motivating the interest toward the realization of more complex systems where different atmospheric situations are really simulated and controlled.

2. Measurement setup

A BB84 quantum communication protocol^{5,6} experiment was mounted in laboratory, as depicted in figure (1).

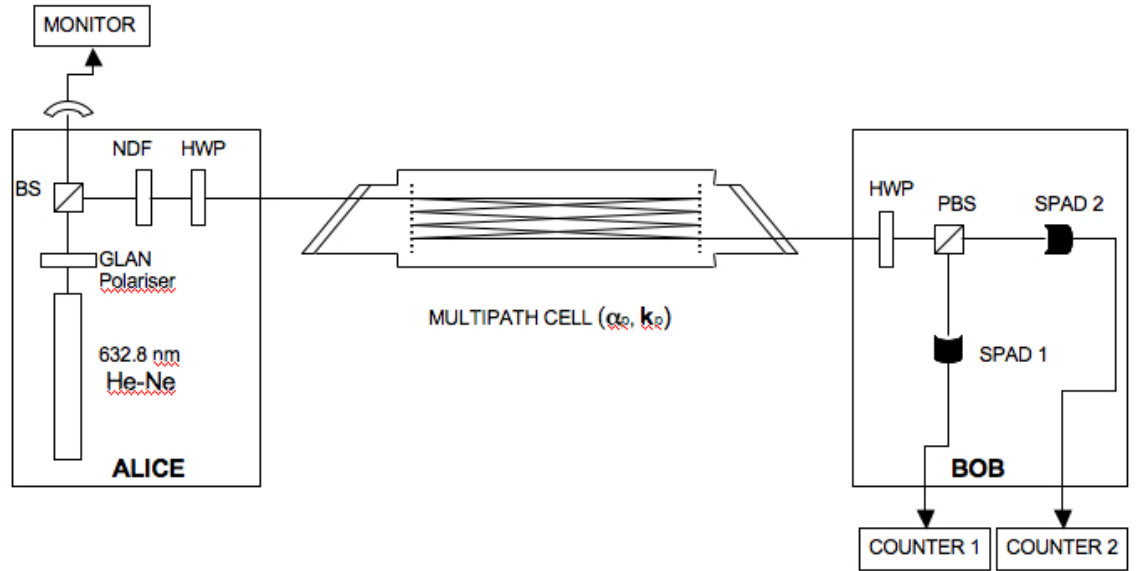


Fig. 1. Schematic of a BB84 quantum communication protocol. Alice is the source of photons. The light of a laser is plane-polarized after the GLAN polarizer and its power is then monitored by measuring the fraction of light split in a beam splitter (BS). The power of the light is attenuated by means of neutral density filters (NDF) and the plane of polarization is chosen by means of a half-wave plate (HWP). The photons in the multipath cell extend their path based on the number of reflections inside the cell; a gas with an extinction coefficient k is inserted into the multipath cell to simulate the atmosphere. Finally the photons reach the receiver Bob. A Half-wave plate (HWP) and a polarizing beam splitter (PBS) allow Bob to choose the bases which the photons are measured in. Two single photon avalanche diodes (SPAD) and their counters measure the number of photons in the two different states of plane polarizations (either horizontal or vertical).

Alice is the source of single photons, Bob is the receiver and the multipath cell is the quantum channel.

The source of light is a 11.3 mW output power helium-neon laser, with a 500:1 plane polarization ratio and a $\lambda = 632.8$ nm wavelength. The laser beam is attenuated by means of neutral density filters down to the photon counting regime. Ideally, single photons are supposed to be used; however, the available ones (PDC heralded photons, quantum dots, color centers in diamond) are not ideal and they can be approximated by low-average-photon-number coherent states (weak laser beams), with the only side effect of a smaller security threshold.

A polarizer guarantees a better polarization ratio of at least 1000:1. Finally a half-wave plate is used to rotate the plane of polarization of the photons.

A multi-path cell was first described by John U. White in 1942⁷. The bulk of a White cell consists of three spherical concave mirrors having the same radius of curvature and positioned to form an optical cavity. Depending on the mutual position of the mirrors, the light is subject to many reflections inside the cavity, hence extending its total path.

At the exit of the cell, the light is directed into a half-wave plate, which can twist the plane of polarization again. A polarizing beam splitter (hence PBS) splits the beam into two different optical channels; the input light, according to the relative polarization, and the exit beams are measured by two identical SPADs, namely the PDM 5CTC model by MPD-Micro Photon Devices with quantum efficiency of 38% @633 nm and 78 ns dead-time.

3. The experiment

Both Alice and Bob dispose of half wave plates and polarizers for setting the transmission and measurement bases (for a presentation of our set-up see fig. 2 and fig. 3).

Alice can simulate 4 states of polarization of light by means of four rotations of her half-wave plate:

- (1) vertical: the half wave plate is in its vertical position,
- (2) horizontal: the half-wave plate is rotated by 45° clockwise,
- (3) left diagonal: the half-wave plate is rotated by 22.5° counter clockwise,
- (4) right diagonal: the half-wave plate is rotated by 22.5° clockwise.

Bob needs two bases: one vertical and horizontal (herein VH), the other, left diagonal and right diagonal (herein LR). The PBS before the single photon counters is a VH basis; in order to have a LR basis, the half-wave plate in front of the PBS is rotated by 22.5° clockwise.

In BB84 protocol, the polarization of the transmitted photon and the basis of the measured photon are randomly chosen. Since our purpose to investigate the effects of the atmosphere on a communication link, we chose to set the halfwave plates in each one of the eight possible positions and to measure the number of photons in each of the two directions.

In a first configuration, the multipath cell was set to vacuum state and the inside mirrors were tilted so that, after many reflections, the path was 22.4 m long ^a. Considering the time discrimination window of the detector equal to their dead-time (78 ns) we arranged the attenuation of the neutral density filters placed in front of the laser so that, for a vertical polarization and a VH basis, the count rate on the single photon receivers were of the order of 10^5 photons/s. Under this condition the average number of photons within the time discrimination window of a detector is $\mu \approx 7.8 \cdot 10^{-4}$ photons.

^aIt is worth mentioning that much longer paths can be obtained with other cells.

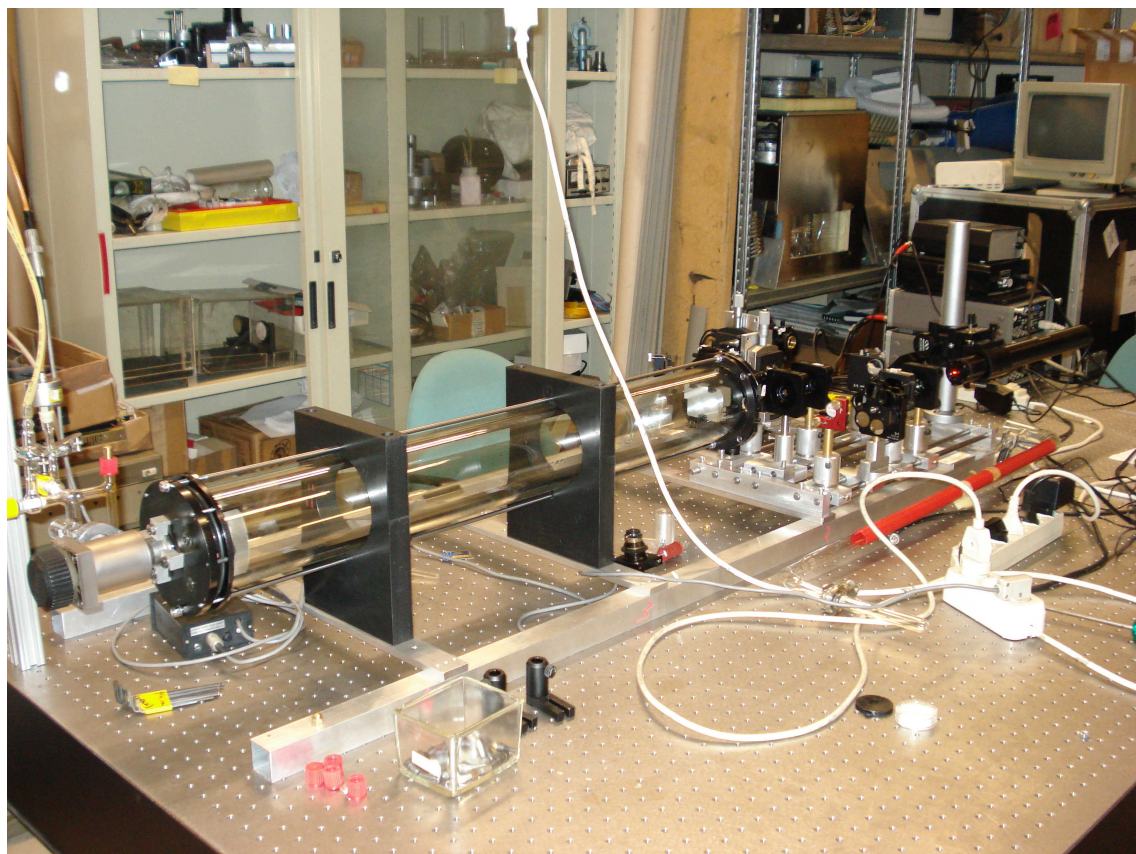


Fig. 2. Picture of the experimental setup assembled in laboratory to test a BB84 protocol through the atmosphere. In the foreground, the transparent multipath cell is seen and in the background the source and receiver are placed.

As we stated before, we intend to demonstrate that in a lab it is possible to simulate the effect of the atmosphere on a quantum communication protocol; the main effect of the atmosphere is the absorption of the signal which lowers the useful photon counts making it more and more equal to the dark counts and lowering the reliability of the communication link. Thus, as a second step, bromine was injected into the cell and the measurements were repeated. Bromine is chosen because it has a high molar absorptivity at $\lambda = 632.8 \text{ nm}$; that will reduce the useful signal making it comparable to the dark counts. In such a case, the error rates would be more significant and the effect of the atmosphere can be shown.

4. Results

The QBER is defined as the ratio of the amount of photons detected with the wrong polarization to the total amount of detected photons. It derives both from optical

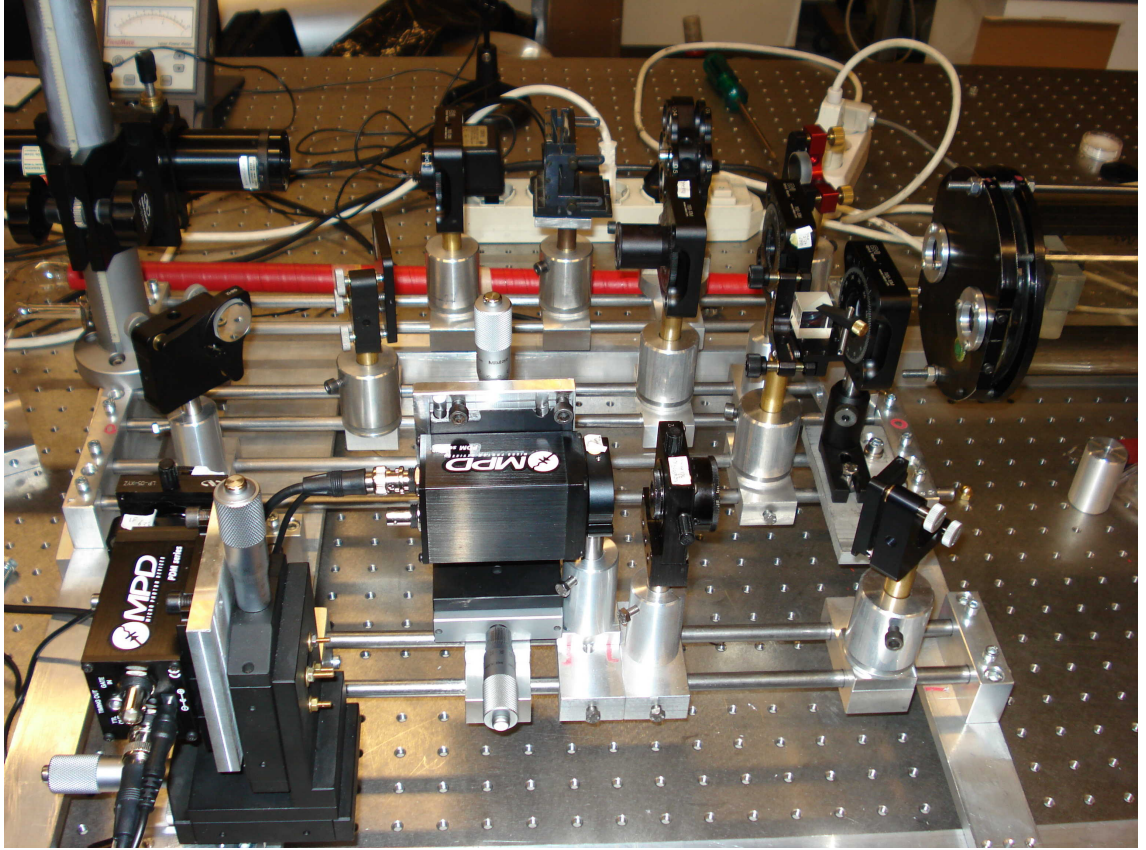


Fig. 3. Detail of the experimental setup: the source is placed far from the camera, while the receiver setup can be seen closer.

imperfections and from the effects of the communication channel.

When the cell is placed in vacuum state (the pressure is less than 1 hPa), the mean measured QBER was 0.86%. This is only due to imperfections of the optical instruments. The polarization ratio of the polarizer is 1000:1, so we can consider our light in a state of plane polarization for our purposes.

Afterwards, 30 ml of bromine was injected into the cell (the bromine molar absorptivity is $\epsilon = 1.3 \text{ cm}^{-1}(\text{mol/L})^{-1}$ ⁸). In the vacuum, it evaporates, filling the whole cell, until a pressure of 26 hPa is reached. The measurements are then repeated.

We first noticed that, only 1% of the previous amount of photons are transmitted through the bromine dioxide and counted by the SPADs.

In this condition the QBER was 7.68%. A value approaching the security limit of BB84 which is 11 %, a result showing the feasibility of a simulation of atmospheric effects in lab.

Let us now consider the extinction coefficient k . If P_0 is the power of the beam at the receiver when there is vacuum in the cell and P is the power of the beam at the receiver with the bromine inside the cell, we measured $\frac{P}{P_0} = 0.01$. We can then evaluate the length L traveled by the light in different atmospheres (assuming a parallel plane atmosphere⁹), corresponding to the values of k we set in order to obtain the same attenuation, $\frac{P}{P_0} = e^{-kL}$. This allows to estimate what QBER is to be expected in different atmospheres, before the quantum transmission. We have matched the path in an atmosphere to the path in our cell full of bromine, by means of the extinction coefficient. For instance, we can consider an horizontal transmission at ground level under the following atmospheric conditions:

- in a summer atmosphere, with urban aerosols and 5 km visibility, $k = 2.62 \cdot 10^{-1} \text{ km}^{-1}$ and $L = 17.6 \text{ km}$;
- in a summer atmosphere, with urban aerosols and 13 km visibility, $k = 9.01 \cdot 10^{-2} \text{ km}^{-1}$ and $L = 51.1 \text{ km}$;
- in a summer atmosphere, with rural aerosols and 5 km visibility, $k = 4.60 \cdot 10^{-2} \text{ km}^{-1}$ and $L = 100.07 \text{ km}$;
- in a summer atmosphere, with rural aerosols and 13 km visibility, $k = 1.58 \cdot 10^{-2} \text{ km}^{-1}$ and $L = 290.9 \text{ km}$;
- in a winter atmosphere, with urban aerosols and 5 km visibility, $k = 2.54 \cdot 10^{-1} \text{ km}^{-1}$ and $L = 18.1 \text{ km}$;
- in a winter atmosphere, with urban aerosols and 13 km visibility, $k = 8.38 \cdot 10^{-2} \text{ km}^{-1}$ and $L = 52.7 \text{ km}$;
- in a winter atmosphere, with rural aerosols and 5 km visibility, $k = 4.51 \cdot 10^{-2} \text{ km}^{-1}$ and $L = 102.1 \text{ km}$;
- in a winter atmosphere, with rural aerosols and 13 km visibility, $k = 1.55 \cdot 10^{-2} \text{ km}^{-1}$ and $L = 270.0 \text{ km}$.

The description of the different kinds of aerosols used can be found in¹⁰ and the values of the relative extinction coefficient can be obtained by simulation with the MODTRAN program¹¹.

5. Conclusions

We reported on our first approach to model a simple atmosphere in laboratory. The reproduced atmosphere was used to test a BB84 quantum communication protocol in free space. As a preliminary result, we measured the effect of that atmosphere in terms of the absorption and QBER.

Future steps will provide a better description of real atmospheres and the evaluation of their effects on quantum communication in situations representing various meteorological conditions.

5.1. Acknowledgments

This work has been supported by EU project QuCandela, by Compagnia di San Paolo and by Regione Piemonte (E14).

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